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JET-ENGINE EXHAUST NOISE FROM SLOT NOZZLES

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SUMMARY

The acoustic effects of slot nozzles having 14:1 and 100:1 width-to-height ratios were investigated using a full-scale turbojet engine. A jet-augmented flap of 3-foot chord was included in the 100:1 slot-nozzle tests. Directional distribution of sound-pressure level, frequency distribution, over-all sound power, and power-spectrum-level values were obtained and are compared herein with circular-nozzle noise characteristics.

The changes in directional and frequency characteristics that resulted from the use of the slot nozzle were appreciable but not necessarily beneficial. Sound-pressure levels were decreased in the plane that contains the nozzle major axis and the jet centerline and were increased in the plane containing the jet centerline and the perpendicular to the nozzle major axis. The frequency distribution was generally flatter for the slot nozzle than for a circular nozzle (reductions were found at low to middle frequencies, and increases at the higher frequencies). A 3-decibel reduction in total sound power was found for the 100:1 slot nozzle. Addition of the jet flap further reduced the total sound power generated by approximately 1.5 decibels for a total of nearly 5 decibels. The largest reductions resulting from the flap occurred between 60° and 90° from the jet axis. A flap of sufficient length to shield the region aft of the 60° azimuth would be considerably longer than the useful lift-augmentation length.

An analysis of the potential noise generation of slot jets and circular jets, based on fundamental mixing-zone structure, was made. This analysis, using velocity and scale similarity relations shown to be applicable for the two kinds of jets, indicates that the sound power generated by a long slot nozzle should be one-half that for an equivalent-area circular nozzle (3 db less). The experiments showed this to be true for the 100:1 slot nozzle.

INTRODUCTION

Jet aircraft operations are steadily expanding to more diverse airfields throughout the world, and in many airport areas the jet-noise problem has, or soon will, become acute. During the period of strictly military operation of jet aircraft, jet operations near densely populated areas could be controlled. The success of commercial jet operations, however, depends to a large extent on convenient service to these densely populated areas. In addition, widespread interest exists in aircraft that can operate from small airports or even from business areas within cities. Therefore considerable research effort has been directed toward the solution of the exhaust-noise problem, and varying degrees of noise suppression have been accomplished for numerous commerical jet aircraft (refs. 1 to 4).

In successful noise suppressors the exhaust is, in general, divided into segments and spread to an over-all cross-sectional area (exhaust and air) considerably larger than that of a single circular jet having the same nozzle-exit area. Hundreds of nozzles of different geometry have been tried by various investigators, and all of the most effective suppressors depend on increasing the mixing of the exhaust gas with surrounding air. Increased nozzle perimeters coupled with appropriate nozzle-segment spacing increase the inflow of secondary air and cause the jet velocity to be dissipated close to the nozzle with the formation of less large-scale, high-energy turbulence. The process in general reduces the level of low-frequency noise but may shift some of the energy to higher frequencies.

Studies of the effects of some basic nozzle shapes on noise generation show that the directional distribution of jet noise is not rotationally symmetrical for nozzles having long elliptical exits (ref. 5) and long rectangular exits (ref. 6) (lower noise levels were measured in the plane of the major axis of the nozzles). Many suppressor designs utilize elongated sections in the nozzle-exit plane that approach elliptic or rectangular shapes. Multiple sections are generally used and, since mixing interference of adjacent jets occurs (ref. 6), the effects of changes in the dimensions of the individual nozzles are difficult to assess.

Applications of the long rectangular nozzles are also found in some of the proposals for STOL and VTOL aircraft that rely on long slot nozzles with the exhaust directed over the top surface of a wing flap to provide the high lift characteristics required. Air-jet tests of some small-model slot nozzles and jet-flap configurations (ref. 7) showed appreciable noise reductions and large changes in the directivity of the noise as compared with a circular nozzle of the same area. The present full-scale-engine investigation of several slot nozzles has been initiated for the purpose of evaluating the noise-generation characteristics for nozzles of large slot width-to-height ratio, including a jet-augmented-flap configuration.

APPARATUS AND PROCEDURE

Engine and Test Stand

<u>Engine installation</u>. - An axial-flow turbojet engine with rated sea-level thrust of 5000 pounds, an exhaust-nozzle pressure ratio of 1.7, and exhaust-gas temperature of 1275° F at rated conditions was installed in the airframe shown in figures 1 and 2 and was operated with the existing fuel, lubrication, and control systems.

<u>Engine instrumentation</u>. - Thrust measurements were made by means of a temperature-compensated strain-gage tension link located in the restraining cable. No direct airflow or fuel-flow measurements were made. However, since airflow is a function of engine speed, the airflow was calculated for the standard conical nozzle, and the resulting calibration curve was used for the other nozzles. Engine speed and exhaust-gas temperature and pressure were measured.

<u>Engine operation</u>. - The engine was operated over a range of power settings from 50 to 100 percent of the full-power condition. Engine performance data were obtained at from three to five engine-power conditions.

Exhaust Configurations

<u>Nozzles</u>. - Two wedge-shaped exhaust nozzles having converging cross-sectional-area transition from the circular-turbine-flange diameter to the rectangular slot-nozzle exit were used in the investigation. In addition, one conical convergent nozzle referred to as the "standard nozzle" was used as a basis for comparison. All the nozzles were nominally 2.1 square feet in exit area. The slot nozzles were slightly larger to take into account the lower coefficient of discharge. The slot nozzles had width-to-height ratios of 14:1 (66 by 4.6 in.) (shown in fig. 1) and 100:1 (180 by 1.8 in.) (fig. 2).

<u>Jet flap</u>. - A sketch of one of the possible ways of using the jet flap for lift augmentation is illustrated in figure 3. Small engines, submerged in the wing, exhaust through slots and over the flap surface. This configuration was simulated by mounting a sheet-metal panel on a channel section frame alongside the 100:1 nozzle opening with the nozzle in the vertical position, as shown in figure 4. The panel measured 3 by 16 feet and was alined parallel to the flow. The flap was slightly wider than the 15-foot nozzle opening, and the 3-foot chord gave a chord-length-to-slot-height ratio of 20. This value of chord-length ratio is considerably greater than the optimum length for the jet-deflection requirement (ref. 8) but is far short of the value of 190 used for the best acoustic results given in reference 7.

Acoustic Measurements

Acoustic measurements were made in 15° increments at a radial distance of 200 feet from the nozzle exits, as shown on the sound-field diagram (fig. 5). Measurement stations were located over a 120° sector on one side of the engine only, 15° to 135° from the jet axis. Microphone height for all measurements was 8 feet above ground level. No measurements were made on the other side of the engine nor directly forward because of the proximity of another engine stand to the side and fuel trailers forward.

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The sound field was free from large reflecting surfaces other than the ground (turf and concrete), and the nearest large building was located approximately 500 feet in front of the engine. Ground-reflection effects are present in particular frequency bands (ref. 9); however, the effects tend to average out because the jet is a distributed source rather than a point source of noise.

Sound-pressure-level measurements were made at each measurement station for several power conditions for each configuration. Spectrum levels were obtained at all measuring stations for one engine-power condition. Sound-level measurements were made with a commercial sound-level meter and a condenser microphone. Frequency distributions were measured with an automatic audiofrequency analyzer and recorder also equipped with a condenser microphone. The analyzer was mounted in an acoustically insulated truck, and direct field records were taken. Both instruments were calibrated before each test by using a small loudspeaker-type calibrator and a transistor oscillator.

The acoustic terms and symbols used herein are defined in the appendix.

RESULTS AND DISCUSSION

The results obtained are confined primarily to acoustic characteristics of the slot nozzles and the jet-flap configuration. For this investigation the engine was used only as a source of high-temperature, high-pressure gas. Performance data were obtained but are of minor significance other than for use in correcting the acoustic data to a particular effective jet-velocity condition (1600 ft/sec was selected as the reference value). Effective jet velocity was calculated from mass-flow rate through the engine and measured thrust.

Standard Nozzle

The acoustic characteristics of the standard (conical convergent) nozzle are presented with the other results wherever possible for ease of comparison. Over-all sound power radiated by the standard nozzle was 165 decibels for the 1600-foot-per-second jet-velocity condition.

Slot Nozzles

Acoustic results are presented in the form of: (1) polar plots showing the directional distribution of sound pressure about the engine, (2) spectrum-level distribution at three azimuths, 30°, 90°, and 135° from the jet axis, and (3) power-spectrum-level distribution. Directionality and spectrum levels are presented for two orientations of the nozzles (slot horizontal and slot vertical). Total-sound-power and power-spectrum-level values were obtained by considering one-half of the sound to be radiated at the levels measured with the nozzles horizontal and the other half at the levels measured with the nozzles in the vertical position.

The primary variable in jet-noise generation is jet velocity; therefore, all the acoustic results were corrected to the reference jet velocity (1600 ft/sec). For sound-radiation patterns that are rotationally symmetrical about the jet axis (standard circular nozzle), the correction is based simply on the experimentally determined relation of sound power and jet velocity. The same procedure is used for the slot nozzles, but the correction is applied for each orientation of the nozzle. The method used consisted of calculating sound power from the measured sound-pressure levels for each nozzle orientation, with rotationally symmetrical radiation about the jet axis assumed. These sound-power values do not represent the actual total sound power radiated but are the proper values to use for making the corrections for a particular nozzle orientation. Corrections to spectra and polar plots assumed equal level shifts at all frequencies and azimuths. The amount of the correction was never more than 2 decibels.

14:1 Slot nozzle. - Figure 6 shows the results obtained for the 14:1 slot nozzle with the long axis: (1) parallel (nozzle horizontal), and (2) perpendicular (nozzle vertical) to the measurement plane.

Directional distribution of sound-pressure level, presented in figure 6(a), shows 1- to 7-decibel reductions from the standard-nozzle results for the slot nozzle in a horizontal position and 3- to 5-decibel increases over most of the sound field for the nozzle mounted vertically. The location of the peak sound-pressure level is shifted to the 45° azimuth from the usual 30° location for the standard circular nozzle.

Over-all sound power, determined from an average of the horizontal and vertical results, was within approximately 0.5 decibel of that for the standard nozzle (165 db). This result is not particularly significant except that it shows the sound to be redirected rather than changed in over-all magnitude.

Spectrum levels are shown in figures 6(b) to (d) for the three azimuths. At the forward (135°) and 90° azimuths the spectra are similar to that for the standard nozzle, with higher levels (particularly at the higher frequencies) for the nozzle vertical, and reductions in the high-frequency content for the nozzle horizontal. To the rear of the engine (30° azimuth) 2- to 8-decibel reductions at frequencies up to 250 cycles per second were measured for the horizontal orientation. Dips and peaks in the spectral distribution over several frequency bands result from ground-reflection effects (ref. 9).

Power-spectrum level (fig. 6(e)) shows the average of the two orientations of the nozzle to be very similar to the standard nozzle results, but with higher levels at frequencies above 200 cycles per second.

100:1 Slot nozzle. - Large differences in the directional distribution characteristics of the 100:1 nozzle exist as a function of nozzle orientation, as evidenced by the polar plot (fig. 7(a)). With the nozzle mounted vertically, the sound-pressure levels are similar to that of the standard nozzle over most of the sound field. The reductions in level at the 15° and 30° azimuth result in a shift of the location of the maximum level to the 45° azimuth. Horizontal orientation of the nozzle resulted in sound-pressure-level reductions (compared with the standard nozzle) of 6 to 20 decibels from the 60° azimuth aft, and reductions of from 2 to 5 decibels at all measuring stations forward of the 60° azimuth. The maximum sound-pressure level occurred at the 75° azimuth, a shift of 45° from the maximum for the standard nozzle.

Spectrum levels for the three azimuths, 30°, 90°, and 135°, are shown in figures 7(b) to (d). At all three azimuths both orientations of the slot nozzle show flatter spectral distributions than the standard nozzle and thus have a greater proportion of high-frequency noise. At the 30° azimuth differences of from 11 to over 30 decibels exist between the spectrum levels for the two orientations of the nozzle over the entire spectrum range, with the largest differences occurring above 400 cycles per second.

The total sound-power level was reduced slightly (3 db) from that for the standard nozzle. Directional and frequency changes in the noise radiation are the important considerations; however, the 3-decibel change in sound power shows that some suppression of the noise does occur.

The averaged sound-power spectral distribution, shown in figure 7(e), further emphasizes the differences in the noise-generation characteristics of the slot and circular nozzles. Decreasing the low frequencies and increasing the high frequencies usually result in an increase in the noise annoyance, particularly for increases in frequencies in the range of greatest sensitivity of the ear. Subjective evaluation of such frequencies would result in equal loudness at lower actual sound-pressure levels as compared with frequencies in the order of 100 cycles per second.

Jet-Flap Nozzle

The acoustic characteristics of the 100:1 slot nozzle with the jet flap are shown in figure 8 and are presented for both sides of the sound field. The left side contains the flap or shield and is referred to as the "shield side" of the sound field, and the other side is referred to as the "jet side." For purposes of comparison the results obtained for the 100:1 slot nozzle alone and for the standard nozzle are included.

Directional distribution of sound-pressure level is shown in figure 8(a). Appreciable differences exist between the shield side and the jet side of the sound field with marked reductions in sound-pressure level on the shield side from the 60° to 90° azimuths. The flap was not long enough to shield the portion of the sound field aft of the 60° azimuth, and consequently the highest levels occur in this region. The effect of the flap on the opposite sound field (jet side) was negligible, as the average variation from the results obtained without the flap was approximately 1.5 decibels and the maximum variation was 3 decibels.

A comparison of the spectrum level at three azimuths (figs. 8(b) to (d)) shows that the shield provides reductions referred to the slot nozzle alone at the 90° and aft azimuths, particularly at frequencies over 1000 cycles per second. However, the levels are still substantially higher than for the standard nozzle at the higher frequencies.

Total radiated sound power is not a particularly useful parameter for evaluating nozzles designed to direct noise away from the observer, but it is included along with power-spectrum level for comparison with other nozzles. A value for the over-all sound power was obtained from the average of the sound powers calculated for the jet-flap nozzle in the vertical position and for the slot nozzle in the horizontal position. The value so obtained is 160 decibels, indicating a reduction of approximately 1.5 decibels as a result of the addition of the flap and a total of approximately 5 decibels less than the standard nozzle. The approximation resulting from the averaging process is probably no better than ± 1 or 2 decibels on the absolute value of sound power, but the comparison based on the slot nozzle alone should be somewhat more accurate. The reduction is not indicative of the difference experienced by the observer but does show that the noise is reduced as well as being redirected.

Power-spectrum level for the jet-flap nozzle is shown in figure 8(e). Comparison with the data from figure 7(e) shows that the addition of the jet flap resulted in lower levels at all frequencies except in the range from 200 to 315 cycles per second.

ANALYSIS

Through the work of Lighthill (refs. 10 and 11), some insight into the mechanism of the jet-noise-generation process has been gained. However, the means of changing the noise-generation process to reduce noise has resulted almost entirely from experimental studies. Some theories concerning the requirements for an effective suppressor have been advanced, but as yet the means of relating noise suppression to changes in the turbulence parameters have not been successful. Much early research work was aimed at reducing the shear gradient at the edge of the jet. Shear gradient in itself, however, has been shown to be a less important parameter than core velocity (refs. 12 and 13). For a particular value of thrust and nozzle-exit area, a reduction of the shear gradient is accompanied by an increase in core velocity. Thus the noise-suppression effect of a reduction in the shear gradient in all probability is offset by a proportionate increase in the length and consequently of the volume of the noise-producing turbulence region. It is generally conceded that noise reductions of significant value result mainly from spreading the jet so as to cause a greater inflow of air and more rapid mixing.

The slot nozzle exposes a large part of the jet to the secondary air by virtue of its large perimeter. In a comparison of a slot nozzle and a circular nozzle of equal area operated under static conditions, several things may be noted concerning the flow: (1) The shear gradient at the nozzle exit is unchanged, (2) the region of highest shear (along the nozzle perimeter) is increased, (3) the core velocity is unchanged, (4) the core length is greatly decreased with mixing completed in a shorter distance (evidenced by visual observation of the jet), and (5) the scale of turbulence (eddy size) is probably reduced. These changes may not necessarily apply to an aircraft in flight because of differences in the external boundary layers, but for the static case they are identical to those associated with replacing a large circular nozzle with many small, widely separated, circular nozzles. In the case of the circular nozzles no change in the total sound power generated occurs, only a change in the frequency inversely proportional to the scaling factor (ref. 5). For the slot nozzle a somewhat different result is indicated if it can be shown that nondimensionalized scale and velocity (mean and fluctuating) relations hold at nondimensionalized distances within the mixing region of the jet for both circular and slot nozzles. These are relations that have been assumed for circular jets by Lighthill, Ribner, and others in analyses of noise-generation processes. Ribner (ref. 14) has shown that a large proportion of the noise is generated in the initial mixing region that extends from the nozzle to the end of the jet core (8 nozzle radii for circular jet), and the discussion to follow is limited to this region.

The relation derived by Ribner from the basic Lighthill equation is given in reference 14 as

$$dW \sim \frac{\rho U^8 dV}{c^5 L} \tag{1}$$

and requires that

$$U = U_0 g_1\left(\frac{r - R}{x}\right) \tag{2}$$

$$(u')^2 = U_0^2 g_1\left(\frac{r - R}{x}\right) \tag{3}$$

$$\overline{uv} = U_0^2 g_3\left(\frac{r - R}{x}\right) \tag{4}$$

etc.

and

$$L = x g_4\left(\frac{r - R}{x}\right) \tag{5}$$

Scale and velocity relations for the two kinds of nozzles (slot and circular) can be demonstrated by some comparisons of experimental results reported in references 15 to 17. Diagrams of the jets (fig. 9) show the use of the symbols. Figure 10 shows the almost exact similarity of the dimensionless local velocity profiles for slot nozzles and a circular nozzle at two nondimensionalized downstream distances. The comparison of dimensionless fluctuating velocities or turbulent intensity is not quite so straightforward because of what appears to be a Mach number effect. Even if the variation with Mach number shown is not truly a Mach number effect but is a result of proportional changes in the upstream turbulence as indicated in reference 15, the result is the same. However, extrapolation from the two circular-nozzle curves shown in figures 11(a) and (b) indicates that good agreement both as to profile and level should result for the slot and circular nozzles at comparable Mach numbers for the two downstream distances. Further confirmation of the similarity is indicated from a Mach number extrapolation of the circular-nozzle results shown in figure 11(c). The region between corresponding curves is the nondimensional area, perpendicular to the nozzle-exit plane, having 13 percent or greater turbulent intensity. Good agreement is again indicated for the two types of nozzles at comparable Mach numbers.

The final comparison to be made, that of the scale of turbulence, is presented in figure 12. Data for this comparison were obtained from references 15 and 16 for a slot nozzle of width-to-height ratio of 3.14:1, which was the only slot-nozzle data available, and a circular nozzle. An eddy-size parameter Λ_x, which is approximately proportional to L_x, is presented as a function of downstream distance. The agreement is within 20 percent throughout the range under consideration. The data presented are for longitudinal scale only, as no lateral-scale data were available for slot nozzles. All the nondimensional velocity and scale parameters for the two kinds of nozzles show reasonable similarity and therefore establish that the slot jet follows the same similarity laws as the circular jet (eqs. (2) to (5)). The proportionality indicated in

$$dW \sim \frac{\rho U^8 dV}{c^5 L}$$

refers to volume elements of dV along a ray of similarity, $(r - R)/x$ = constant. Therefore, (1) may be rewritten as

$$dW = g_5\left(\frac{r - R}{x}\right) \frac{\rho U^8}{c^5 L} dV \tag{6}$$

and, for corresponding rays in the slot-jet and circular-jet initial mixing zones,

$$g_5\left(\frac{r - R}{x}\right) = g_5\left(\frac{y - w}{x}\right)$$

The volume of an annular element of the mixing region of the circular jet is

$$dV_c = 2\pi r \; dr \; dx = 2\pi R \; dr \; dx \; \frac{r}{R} = 2\pi R \; dr \; dx\left(1 + \frac{r - R}{R}\right)$$

An appropriate change of variables allows the expression to be put in the form

$$dV_c = 2\pi R \left(1 + \frac{r - R}{R}\right) x \; d\left(\frac{r - R}{x}\right) dx$$

Sanders shows in reference 18 that the region of by far the greatest importance in the generation of noise is that for $(r - R)/R \ll 1$. If, now, the region under consideration is confined to $(r - R)/R \ll 1$, the volume of annular element may be approximated by

$$dV_c \approx 2\pi R x \; d\left(\frac{r - R}{x}\right) dx$$

By utilizing the similarity relations (2) to (5), equation (6) becomes

$$d^2 W_c \approx 2\pi\left(\frac{\rho U_0^8}{c^5 L}\right) R x \; g_5\left(\frac{r - R}{x}\right) \frac{g_1^8\left(\frac{r - R}{x}\right)}{g_4\left(\frac{r - R}{x}\right)} \; d\left(\frac{r - R}{x}\right) dx \tag{7}$$

For a slot sufficiently long to neglect the ends, the volume element is

$$dV_s = 2Z\ dy\ dx$$

and

$$d^2W_s \approx 2\left(\frac{\rho U_0^8}{c^5 x}\right)Zx\ g_5\left(\frac{y - w}{x}\right)\frac{g_1^8\left(\frac{y - w}{x}\right)}{g_4\left(\frac{y - w}{x}\right)}\ d\left(\frac{y - w}{x}\right)dx \qquad (8)$$

The limits of the mixing zones are 0 to 8R and 0 to 8w (the core length), and

$$r_1 = R - x \tan \alpha, \qquad r_2 = R + x \tan \alpha$$

$$y_1 = w - x \tan \alpha, \qquad y_2 = w + x \tan \alpha$$

or

$$\frac{r_1 - R}{x} = - \tan \alpha, \qquad \frac{r_2 - R}{x} = \tan \alpha$$

$$\frac{y_1 - w}{x} = - \tan \alpha, \qquad \frac{y_2 - w}{x} = \tan \alpha$$

Integrating equations (7) and (8) gives

$$W_c \approx 2\pi R\left(\frac{\rho U_0^8}{c^5}\right)\int_0^{8R}\int_{-\tan\alpha}^{\tan\alpha} g_5\left(\frac{r - R}{x}\right)\frac{g_1^8\left(\frac{r - R}{x}\right)}{g_4\left(\frac{r - R}{x}\right)}\ d\left(\frac{r - R}{x}\right)dx$$

$$W_s = 2Z\left(\frac{\rho U_0^8}{c^5}\right)\int_0^{8W}\int_{-\tan\alpha}^{\tan\alpha} g_5\left(\frac{y - w}{x}\right)\frac{g_1^8\left(\frac{y - w}{x}\right)}{g_4\left(\frac{y - w}{x}\right)}\ d\left(\frac{y - w}{x}\right)dx$$

Using the similarity relation $g\left(\frac{r - R}{x}\right) = g\left(\frac{y - w}{x}\right)$ and dividing gives

$$\frac{W_c}{W_s} \approx \frac{2\pi R\int_0^{8R} dx}{2Z\int_0^{8w} dx}$$

$$\frac{W_c}{W_s} \approx \frac{\pi R^2}{Zw}$$

which is simply

$$\frac{W_c}{W_s} \approx \frac{\text{area of circular jet}}{1/2 \text{ area of slot jet}}$$

and, for a circular jet equal in area to the slot jet,

$$W_c = 2W_s$$

Thus, the sound power generated by a long slot jet is indicated to be half that of a circular jet (3 db less).

The experimental results obtained for the 100:1 slot nozzle show this to be true, whereas such was not the case for the 14:1 nozzle. Presumably, therefore, the 14:1 nozzle is not sufficiently slender to ignore the effect of the ends of the nozzle on the sound generation. The almost exact agreement found for the 100:1 slot nozzle is probably fortuitous, since the averaging technique used for the experimental results would not be expected to have better accuracy than 1 or 2 decibels.

CONCLUDING REMARKS

The noise-suppressing capabilities of a slot nozzle are confined primarily to changes in the directivity and frequency of the noise. The sound-power reduction indicated both in theory and experiment is slight (3 db). The directional changes in the noise distribution are quite large; however, the observed sound levels on the ground either directly under or to the sides of the flight path of an aircraft equipped with a slot nozzle may not be beneficially affected. The reduction in level at the aft azimuths would result in reduced duration of the highest levels along the sides of the flight path. The increased frequency aids in atmospheric attenuation of the noise but may well be more objectionable to the listener.

Addition of the flap to the slot nozzle caused marked reductions in sound-pressure level that in combination with the reduced levels in the horizontal plane would effectively reduce noise levels from aircraft in flight. Flaps of longer chord should be of additional benefit as reported in reference 7. The useful lift-augmentation chord length of the flap is probably not sufficient to give extremely large acoustic benefit; but, by accepting the weight penalty, some compromise chord length could prove satisfactory.

Lewis Research Center
National Aeronautics and Space Administration
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APPENDIX - SYMBOLS AND ACOUSTIC TERMS

Symbols

c	speed of sound in ambient air
f	frequency
$g_1()$, $g_2()$, etc.	functions of ()
L	scale of turbulence
R	nozzle radius
r	radial distance from jet axis
U	mean stream velocity
u,v	fluctuating components of velocity in x, y, or z directions, respectively
V	volume
W	total sound power
w	slot-nozzle-exit half height (short dimension)
Z	slot-nozzle width (long dimension)
x,y,z	right-hand coordinate system with x axis coinciding with jet centerline
α	jet expansion half-angle
ρ	ambient-air density
Λ	characteristic eddy size

Subscripts:

c	circular jet
s	slot jet
x	longitudinal
0	nozzle exit
1,2,etc.	points in stream except for $g()$

Superscripts:

average

root mean square

Acoustic Terms

Sound-pressure level	20 times the $\log_{10}$ of the ratio of root-mean-square sound pressure at a point to reference pressure of 2×10^{-4} dynes/sq cm
Over-all sound-pressure level (all frequencies simultaneously)	obtained directly from sound-level meter using flat-frequency-response setting
Spectrum level	sound-pressure level within specified frequency band of 1-cps width
Sound-power level	10 times the $\log_{10}$ of the ratio of total acoustic power radiated from a source to reference power of 10^{-13} watts (acoustic power is obtained from an integration process (refs. 19 and 20) of sound-pressure levels over a hemispherical region surrounding noise source)
Power-spectrum level	power level at specified frequency band of 1-cps width

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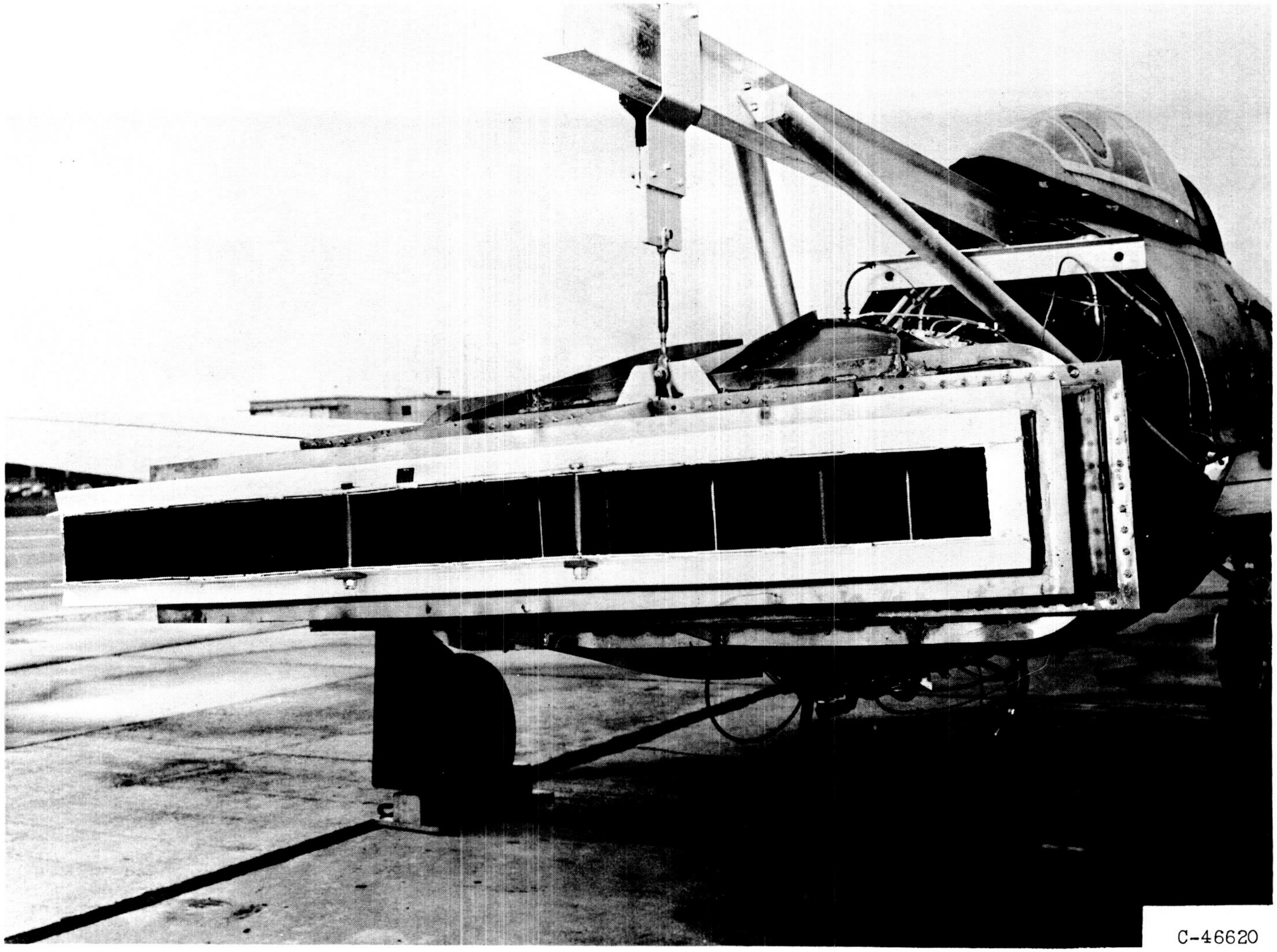
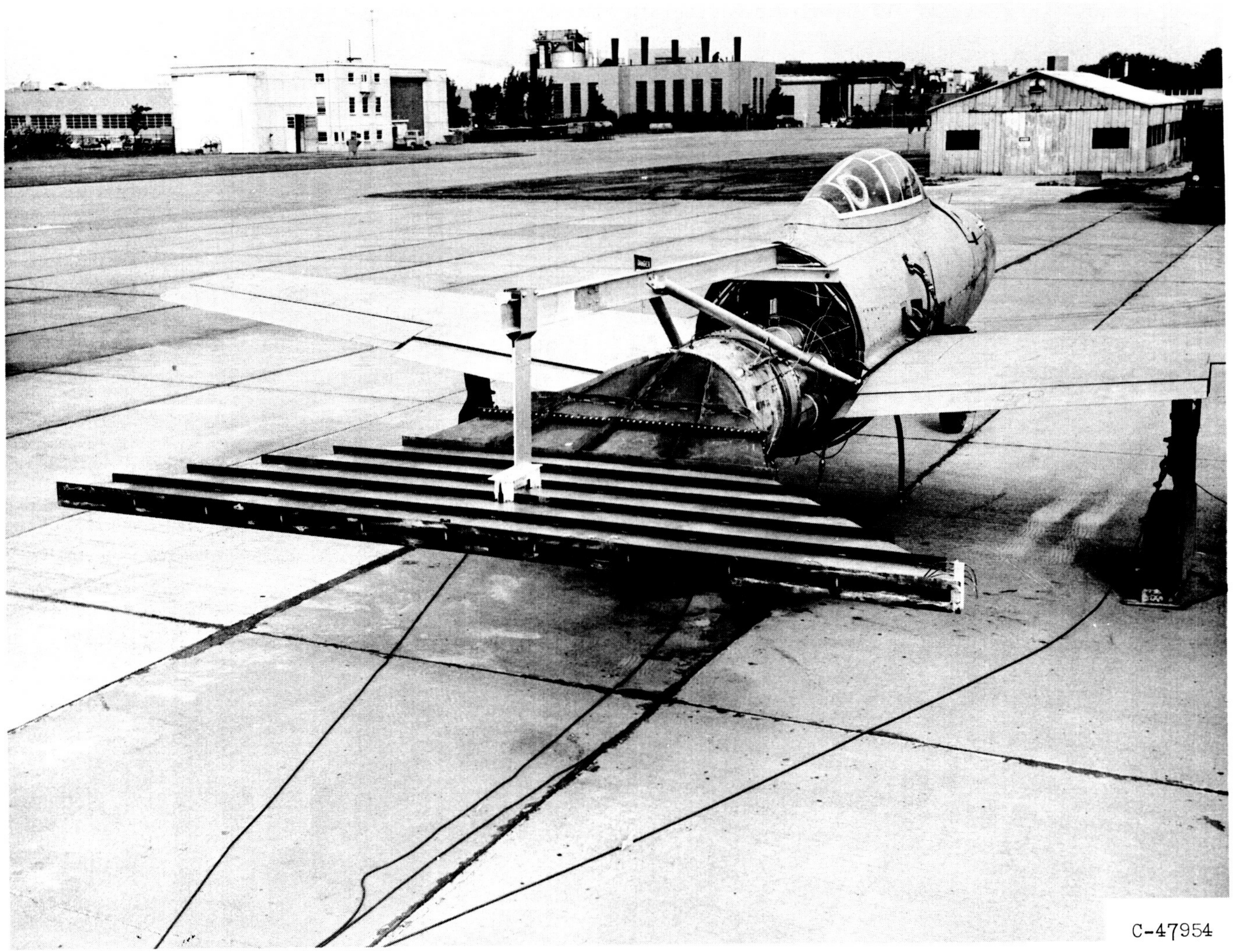
E-374



C-46620

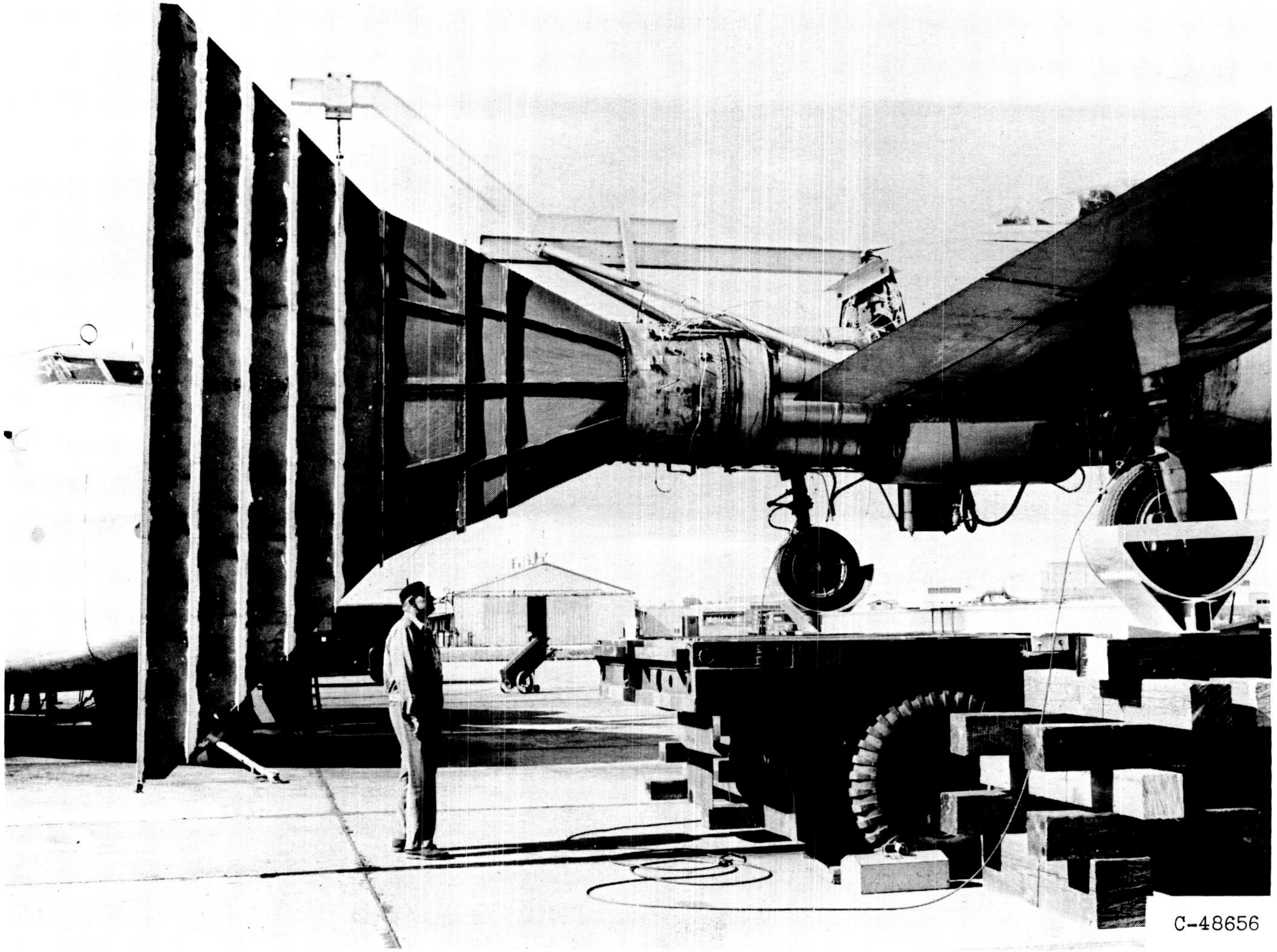
Figure 1. - Slot nozzle, 14:1 width-to-height ratio.



C-47954

(a) Nozzle horizontal.

Figure 2. - Slot nozzle, 100:1 width-to-height ratio.



(b) Nozzle vertical.

Figure 2. - Concluded. Slot nozzle, 100:1 width-to-height ratio.

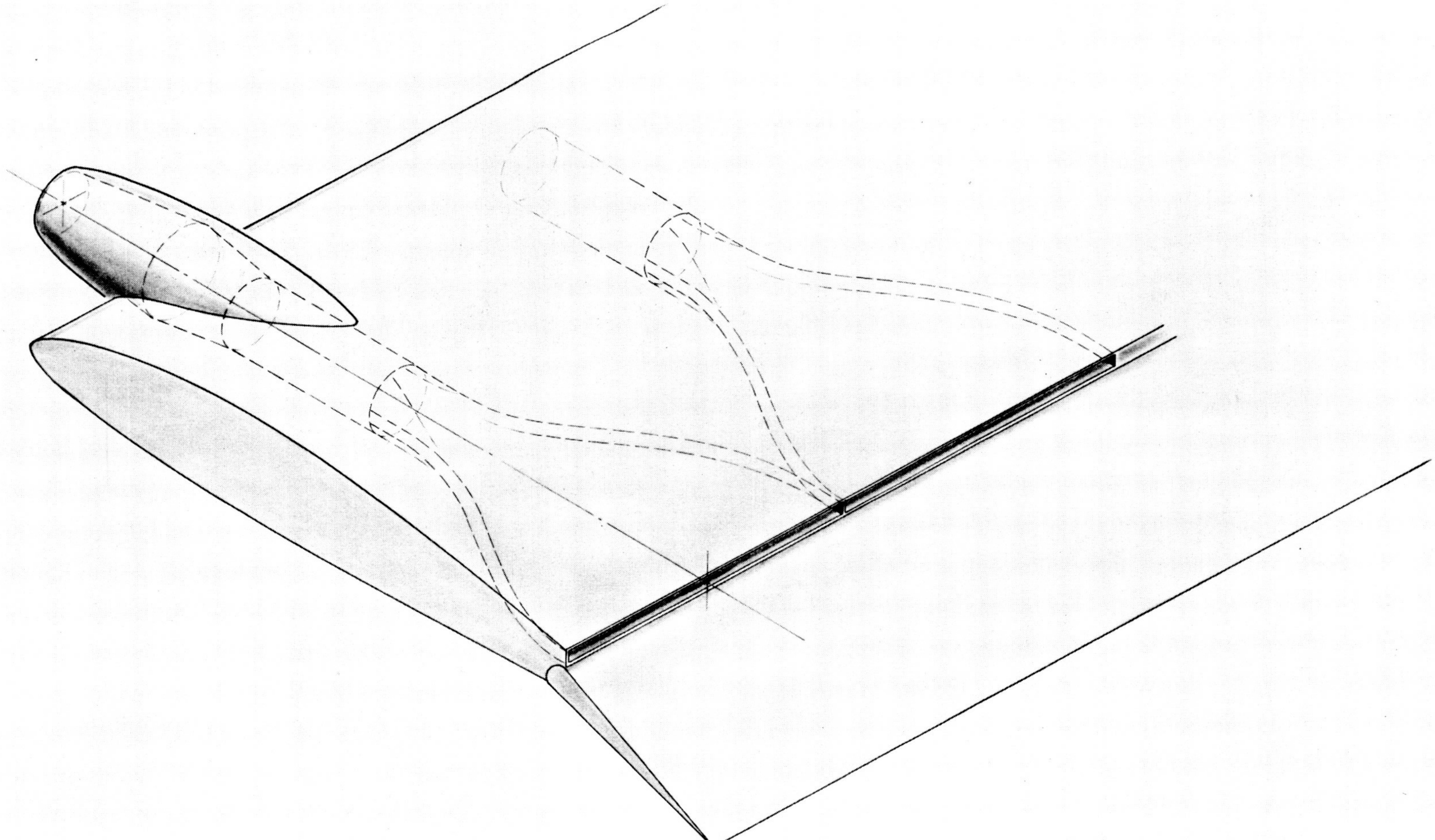


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Figure 3. - Sketch of possible application of jet-flap principle.

Figure 4. - 100:1 Slot nozzle with jet flap.

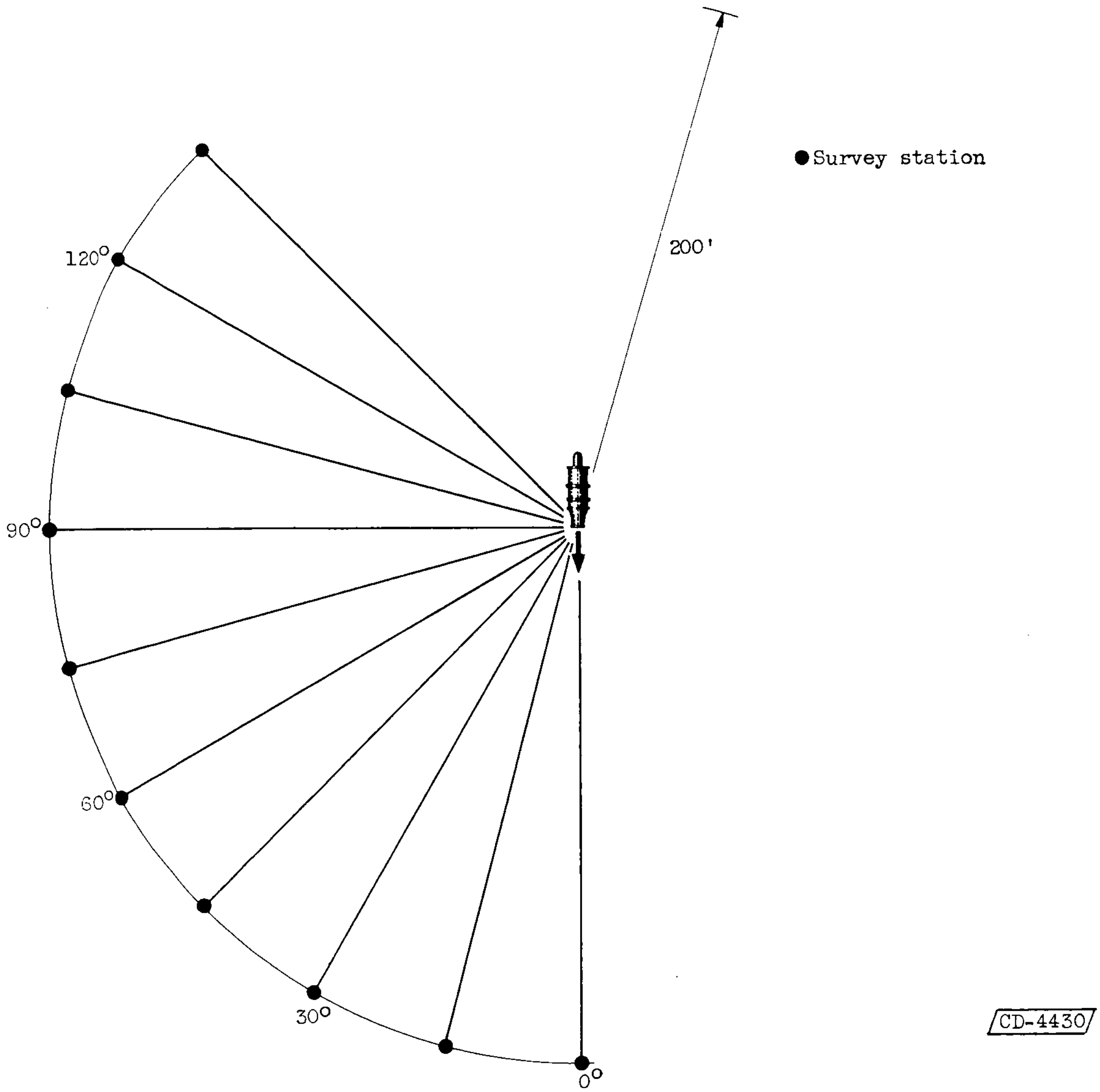

Figure 5. - Planview of engine-sound-survey stations.

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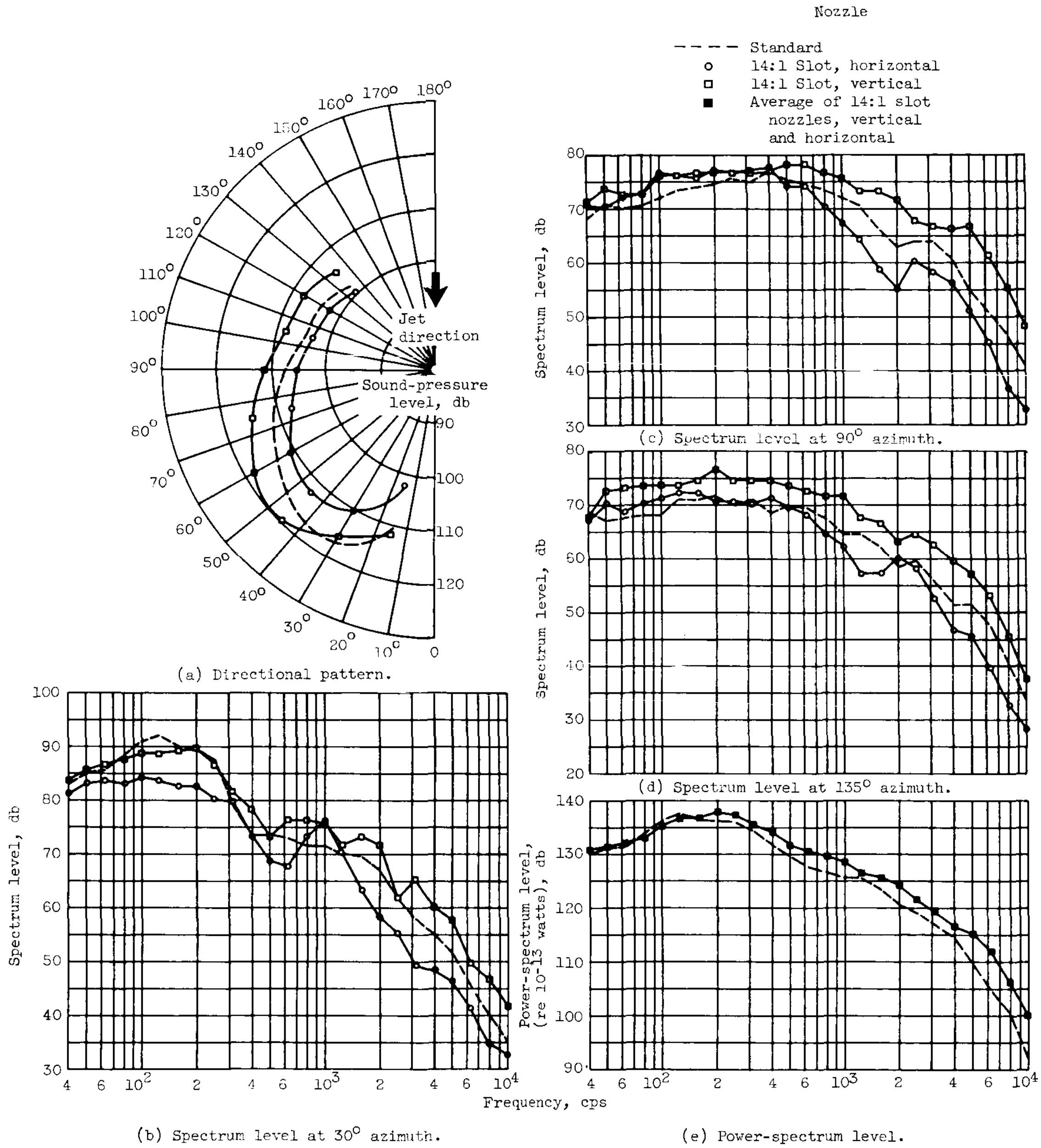
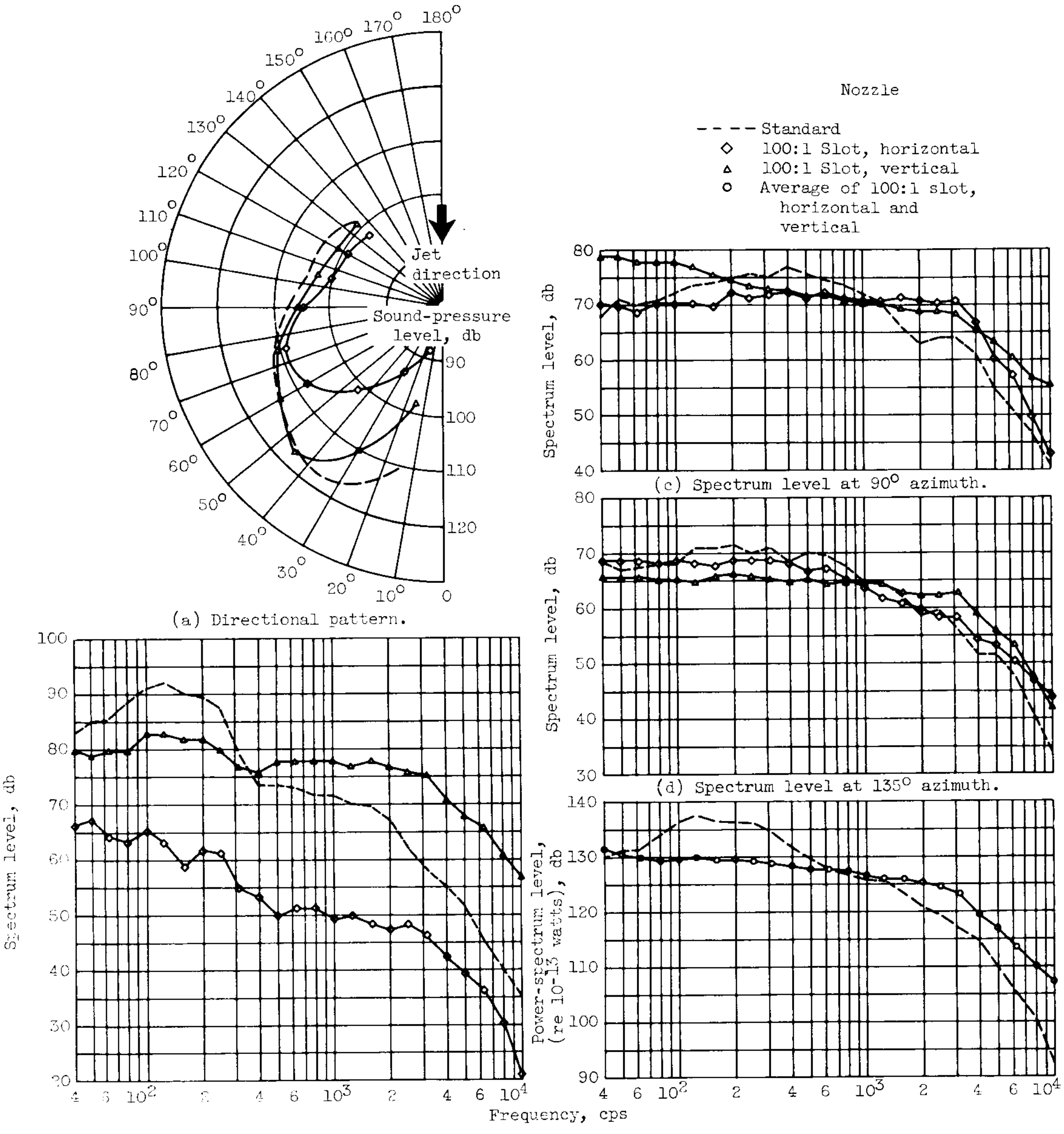


Figure 6. - Acoustic characteristics of 14:1 slot nozzle. Velocity, 1600 feet per second; distance, 200 feet.



(a) Directional pattern.

(b) Spectrum level at 30° azimuth.

(c) Spectrum level at 90° azimuth.

(d) Spectrum level at 135° azimuth.

(e) Power-spectrum level.

Figure 7. - Acoustic characteristics of 100:1 slot nozzle. Velocity, 1600 feet per second; distance, 300 feet.

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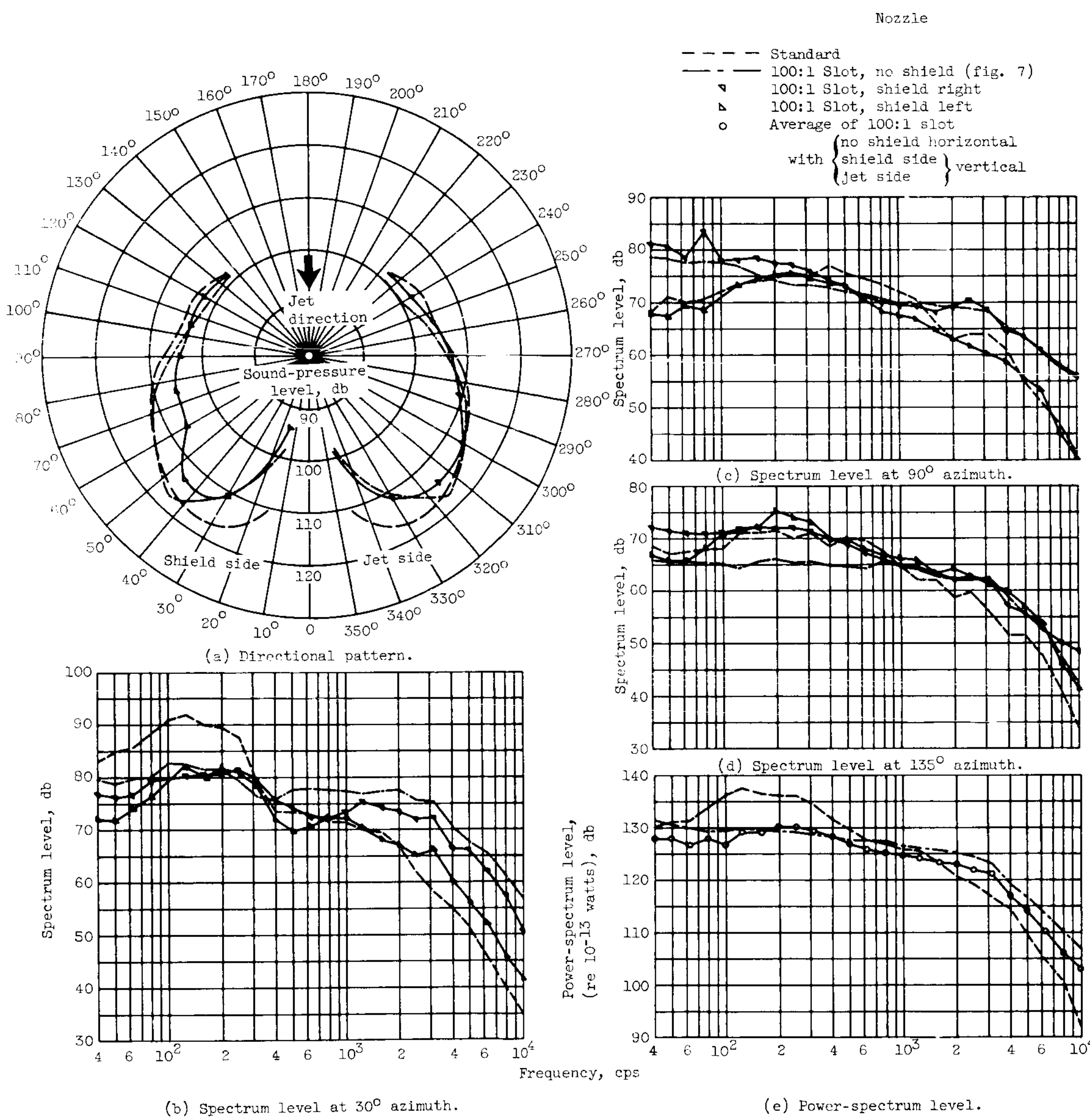
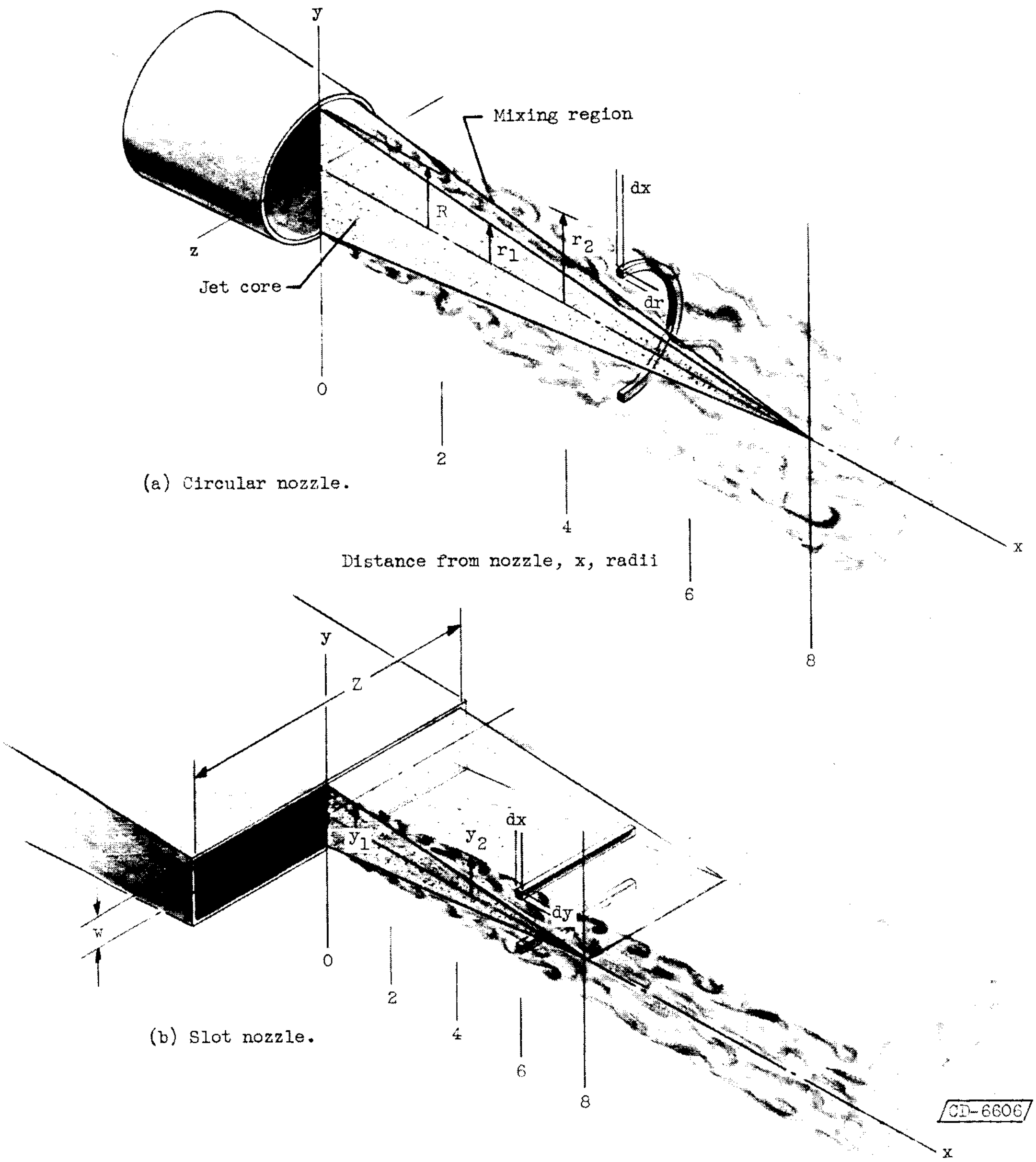


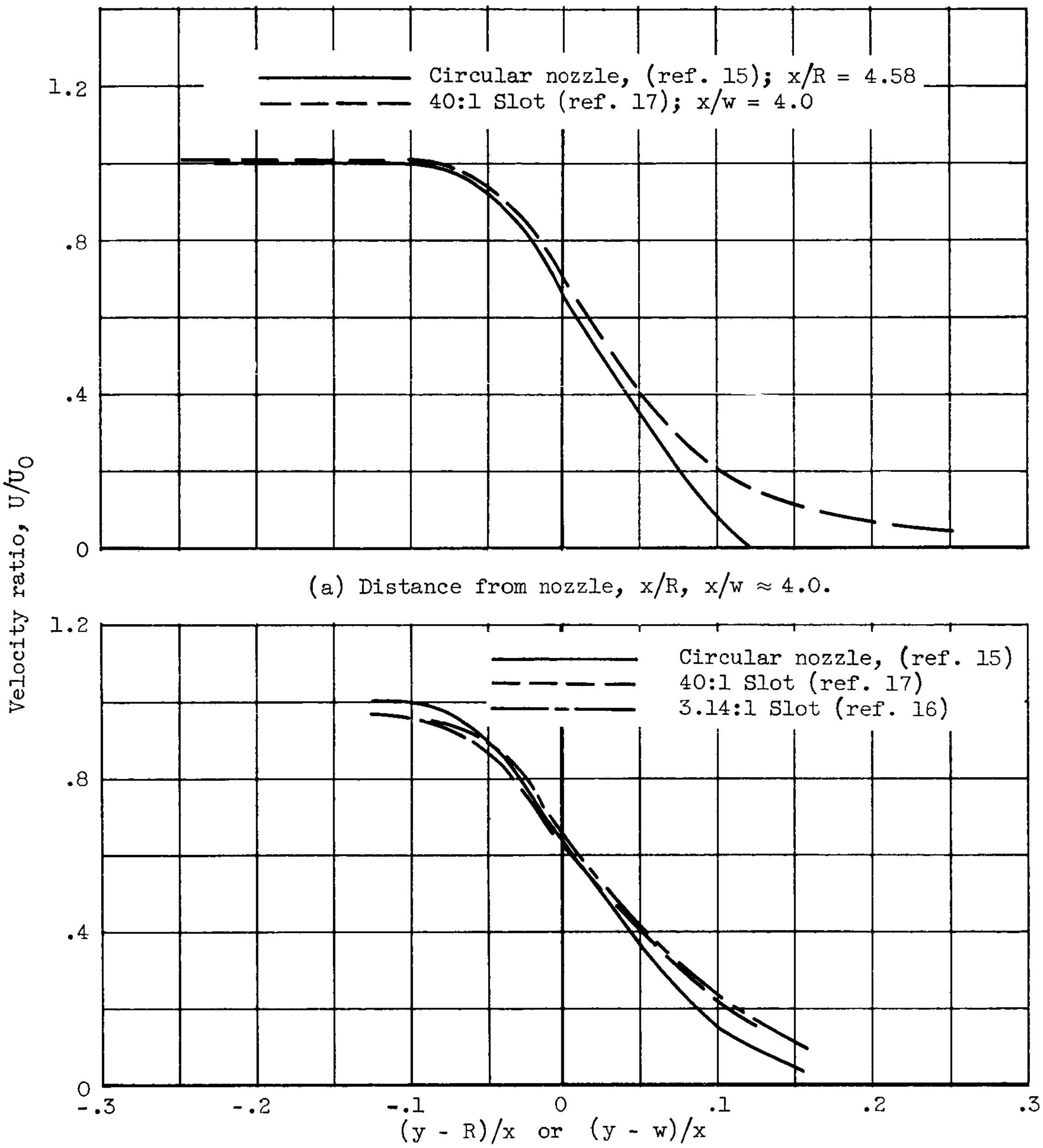
Figure 8. - Acoustic characteristics of 100:1 slot nozzle with jet flap. Velocity, 1600 feet per second; distance, 200 feet.



(a) Circular nozzle.

(b) Slot nozzle.

Figure 9. - Jet-flow diagrams.



(b) Distance from nozzle, x/R, x/w ≈ 8.0.

Figure 10. - Mean velocity profiles.

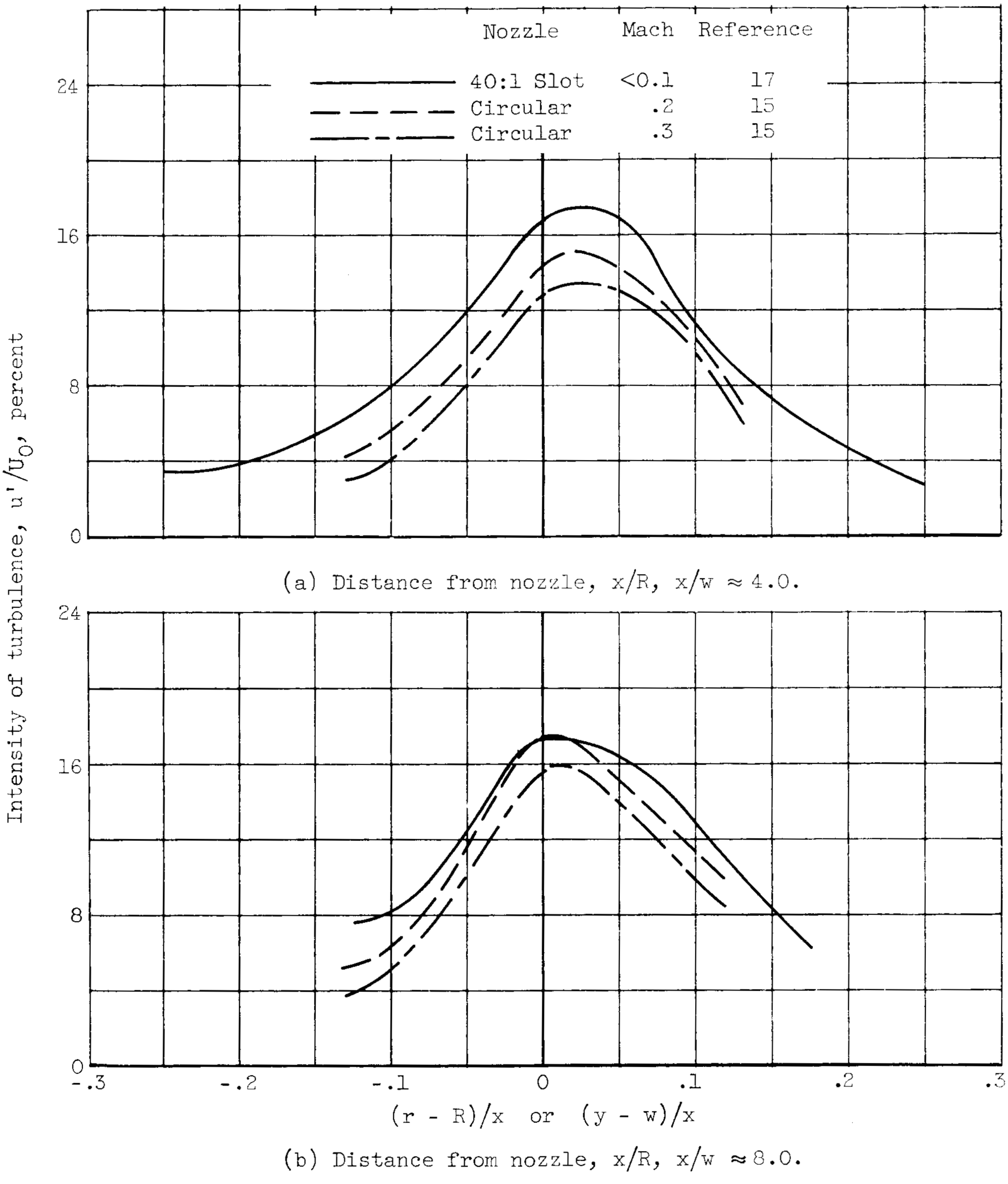
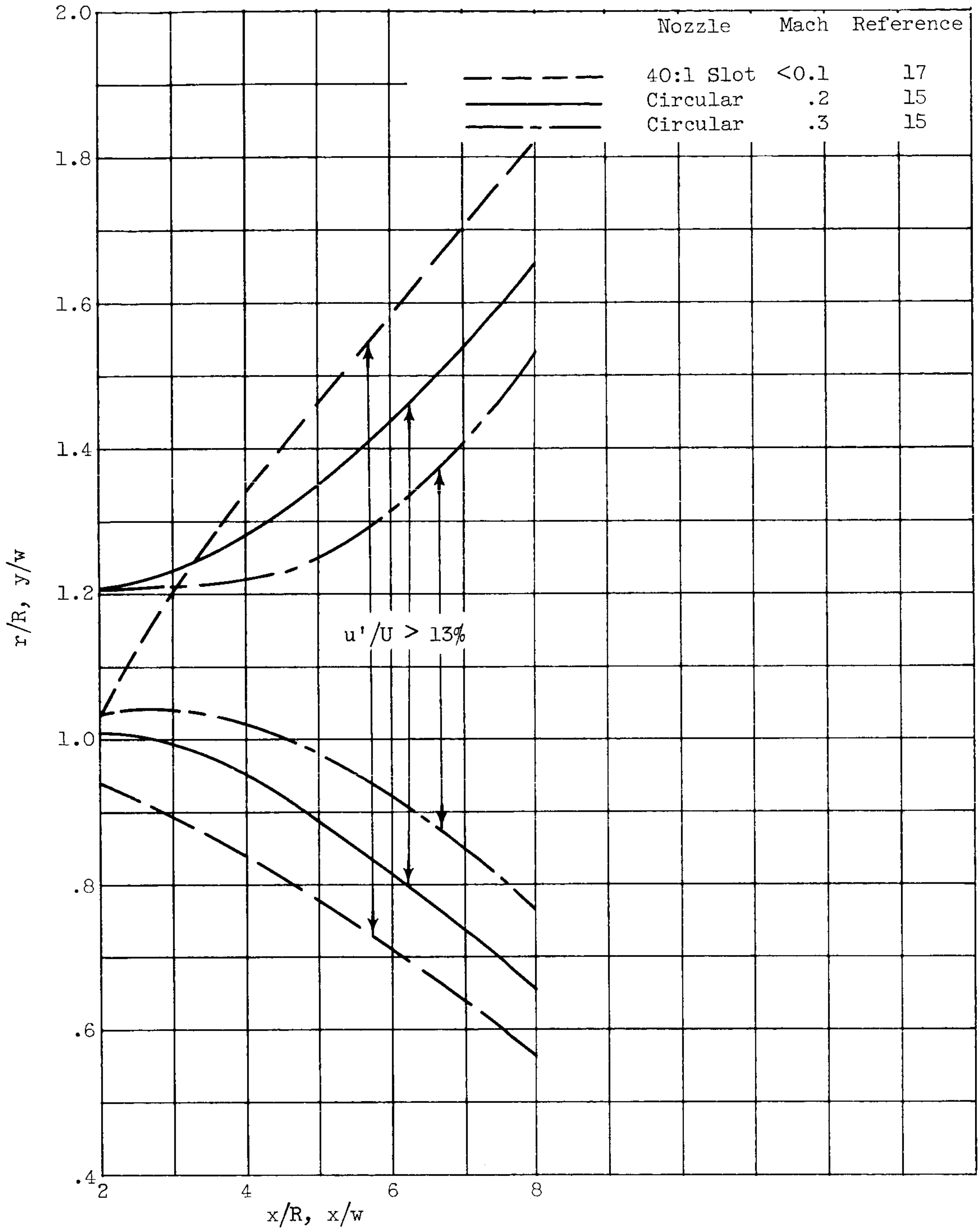


Figure 11. - Intensity of turbulence in percent of nozzle-exit velocity for slot and circular nozzles.



(c) Constant intensity of turbulence profiles (13% of exit velocity) for slot and circular jets.

Figure 11. - Concluded. Intensity of turbulence in percent of nozzle-exit velocity for slot and circular nozzles.

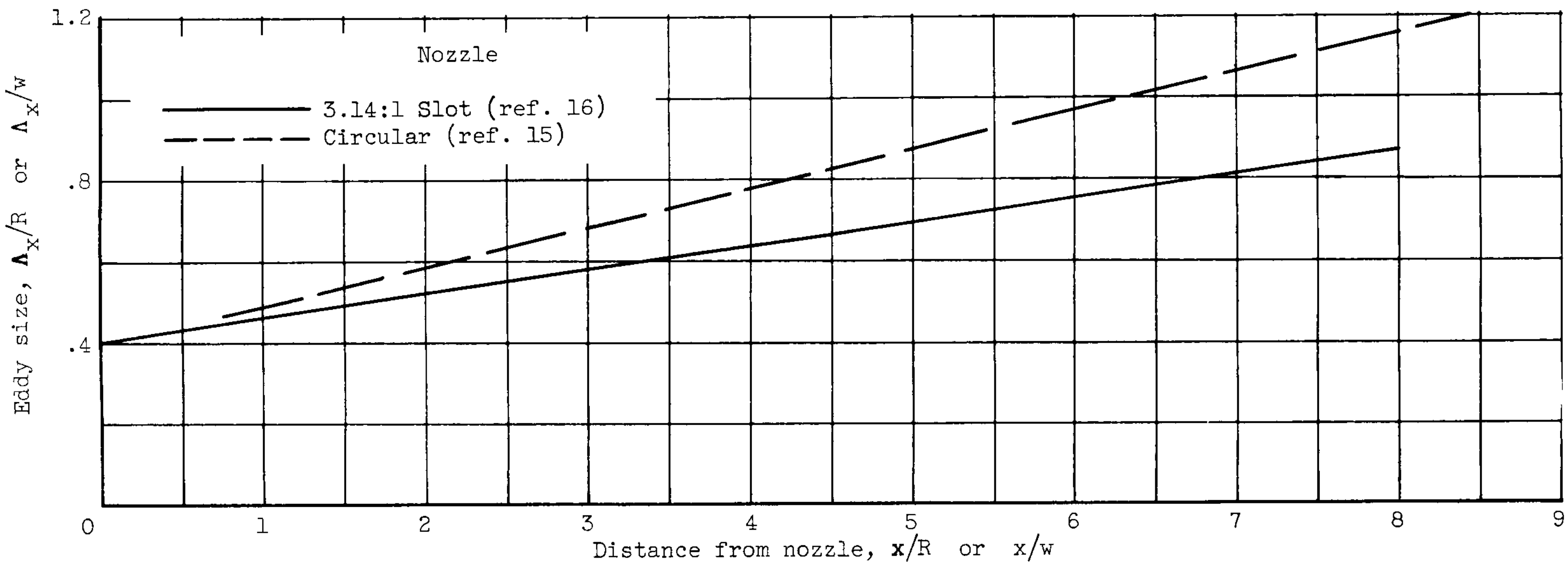


Figure 12. - Variation of dimensionless eddy size with distance from nozzle for circular and slot nozzles. Mach number, 0.3.